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ANISOTROPY AND CRYSTAL STRUCTURE OF THE COCOS PLATE.(U)
AUG 73 G G SHOR, R W RAITT, M HENRY
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Scripps Institution of Oceanography.

(6) ANISOTROPY AND CRUSTAL STRUCTURE OF THE COCOS PLATE*

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ABSTRACT

Seismic studies in two locations on the Cocos Plate, southeast and northwest of the Tehuantepec Ridge, have shown that there is significant anisotropy with the high-velocity direction northeast-southwest and that there is a generally shallow mantle in this area of relatively shallow water and low heat flow. The mantle depth is uniformly about 8 to 8-1/2 km deep between the Clipperton fracture zone and the Guerrero Fracture Zone at 13.5°N. At this point it drops to about 9-1/2 km depth.

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*Contribution of the Scripps Institution of Oceanography, new series.

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INTRODUCTION

Refraction surveys were made of the Cocos Plate in the spring of 1972 by the Scripps Institution of Oceanography and the Hawaii Institute of Geophysics, in a two-ship seismic operation using the research vessels KANA KEOKI and ELLEN B. SCRIPPS. Earlier surveys had been made in 1954 and reported by Shor and Fisher (1961) and Shor, Menard and Raitt (1971) which showed the existence of anomalously shallow mantle at stations near the Tehuantepec Ridge, near the axis of the present East Pacific Rise, and near the axis of the older rise structure to the west.

On this recent investigation, Expedition IGUANA, seismic refraction, reflection, echo sounding and magnetic measurements were made in an area extending from the Carnegie Ridge to Acapulco. In this report we will discuss only refraction measurements that were made in the central portion of the Cocos Plate.

For some time, the Scripps group has been investigating the phenomenon of anisotropy of compressional wave velocity in the mantle, taking measurements in a variety of areas throughout the Pacific and Indian Oceans to determine the extent, amount, and direction of the anisotropy, and its relationship to other tectonic elements.

I should explain for those who have not followed this work closely that Harry Hess originally noticed that there was a curious relationship between the direction in which marine seismic refraction line stations were shot and the velocity computed from these stations for compressional seismic waves in the uppermost mantle. The highest velocities were in directions perpendicular to the magnetic anomalies--or parallel to transform faults. The difference was small, however, and could be explained by other factors. To check whether this relationship was real, and not a fortuitous effect of geographical variations of velocity or of undulations of the Mohorovicic discontinuity, we developed techniques of observation that would provide us with a statistically large number of

observations, well distributed in azimuth, in patterns that avoid the possibility of creation of the time variations by any simple geometry of the Mohorovicic discontinuity. We have applied these techniques in a variety of locations, since that time, and have convinced ourselves that the effect is real.

Since we started gathering these data, several papers have appeared which discuss the possible cause of the phenomenon. The interpretation that we prefer is that by Carter, Baker and George (1972). They and Ave Lallemont have performed both calculations and laboratory experiments that show that anisotropy in the amount that we observe can be produced by syntectonic recrystallization of olivine crystals under conditions of temperature, pressure, and shear that would be found at the top of the mantle near a spreading center. As best we can extrapolate from their laboratory data and papers by Sclater and Francheteau (1970), the appropriate temperatures would occur at the lid of the mantle only within the first few magnetic anomalies. From this we can conclude that the values found in the refraction experiments are "frozen in" from the time shortly after the material solidified. While such anisotropy could be formed in the lower portions of the lithosphere later, we cannot observe such values with present techniques.

Figures 1 through 3 show the results of anisotropy surveys prior to the Cocos Plate work. The first work in the northeastern Pacific (reported by Raitt et al., 1969) showed the high velocity vector nearly at right-angles to the magnetic lineations, and parallel to the fracture zones, as predicted by Hess--but not as large an amplitude of variation as he postulated. The work off Hawaii (reported by Morris et al., 1969) was a large-scale effort that provided strong statistical proof of the reality of the phenomenon, and showed a high-velocity vector nearly east-west. This was not quite perpendicular to the magnetic anomalies, and is definitely not parallel to the alignment of the Hawaiian Ridge. The magnitude of the anisotropy is the second largest found to date.

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The station east of Japan was made to check on direction in an area where a fracture zone (the Hokkaido Fracture Zone) is not orthogonal to the magnetics. In this case the anisotropy is orthogonal to the magnetics, not parallel to the fracture zone.

The stations in the eastern Indian Ocean (figure 3 from Raitt et al., 1972) again show high velocity nearly at right angles to the magnetics.

The stations close to the Galapagos spreading center (Raitt et al., 1971) are confusing--due in part to the fact that they were made prior to good knowledge of the location of the spreading centers, and therefore are not ideally located for getting a clear answer on anisotropy. One of the stations, close to the East Pacific Rise shows strong east-west anisotropy; the other shows none.

As a working hypothesis, we have assumed that the direction of the high-velocity vector is related to the direction of plate movement; it is not clear from data collected thus far, however, whether it is related to the absolute direction of plate movement, the spreading direction, or the plate movement relative to the (possibly moving) spreading center.

At the time that IGUANA Expedition was planned, magnetic lineations 1 through 6 had been delineated along the nearby section of the East Pacific Rise, and along the Galapagos Rift Zone. No older lineations had been delineated in the Cocos Plate, however, so it was hoped that the anisotropy measurements would fill an essential gap in the information regarding the northeastern part of the plate.

FIELD OBSERVATIONS

Three attempts were made to measure anisotropy of the Cocos Plate. The anisotropy station near the Galapagos Rift Zone was, because of problems of equipment and topography, inadequate to give any answers about the anisotropy of the area. The second anisotropy station, station IG-4-5 (reported by Henry et al., 1972) was located in the center of the plate, in the Guatemala Basin, and gave excellent data. The third, station IG-4-8, was in the section of the plate northwest of the Tehuantepec Ridge,

and gave good structural information but marginal (at best) anisotropy results.

The basic pattern for the anisotropy observations was as shown on Figure 4. Each pattern consisted of a set of one-way and reversed profiles, plus "broadside" profiles where the shooting ship followed a course that kept it at a range that would always receive mantle refracted waves as first arrivals, and cover azimuths in a full quadrant of directions. The complete pattern, if all records were usable, would provide a coverage of 7/8 of a circle, with considerable redundancy. The anisotropy experiment has exacting requirements, since the significant deviations from the mean travel time are only 1/4 to 1/2 second, depending on the range. Care had to be taken, therefore, to get records with clear first-arrivals and accurate corrections for topography.

Survey patterns in the ocean rarely turn out exactly as planned, due to effect of wind and current. Careful navigation can, however, result in determinations after the fact of where the observations were taken, which is essential for these surveys that require fairly precise knowledge of both range and bearing between the two ships. Figure 5 shows the actual pattern shot on Station IG 4-5, the station in the center of the Guatemala Basin, and Figure 6 shows the directions of the "broadside" shots on which the anisotropy solutions primarily depend. Figure 7 shows the resultant of the observations as plotted on a 360° azimuth base; Figure 8 shows the same observations reduced to a 180° base by using the reciprocity theorem. The curve is the sine-curve of best fit for the data, and indicates a direction of maximum velocity of 053° and a difference between maximum and minimum velocity of about 0.42 km/sec (5% anisotropy). The same data were used for reversed solutions wherever possible; the results of these solutions (taken individually, without assuming any uniformity of velocity throughout the area) are shown in Figure 9. It should be noted that the depth to mantle is approximately 8 km; extremely shallow compared to oceanic averages.

The next anisotropy station, IG-4-8, suffered from somewhat more effects of drift of the ships (Figure 10), and some lines had to be discarded because of topographic problems; there were, however, sufficient data to get a definitive solution if one could be had. The results of the anisotropy solution were not good; only an optimist would fit the sine curve shown in this figure (Figure 11) to the data obtained. This is the statistical best fit to the data; the reliability of the solution is low. The curve is plotted for the 2 Ø component; there is some evidence that the 4 Ø component (which we have never observed with any reliability elsewhere) may be present. The anisotropy, if one believes it, is at 029°; the amplitude is 0.4 km/sec, as on the previous station.

The structural solutions (Figure 12) from this station were considerably better than the anisotropy solution. Because of the high drift on the station, few of them can be considered truly reversed, so we have plotted here the one-way solutions treating the layering as flat. All stations have been corrected for topography assuming that all of the topographic variation is in the basement layer. Where basement arrivals were not obtained, sediment thickness was assumed to be the same as at nearby stations. No great errors could be caused by this, since the sediments observed, by either reflection or refraction methods, were extremely thin. The stations are plotted here from south to north. The most immediately obvious result, apart from the thinness of the sedimentary section, is the fact that the depth to mantle is uniformly very shallow in the southern stations. The northern stations are consistently somewhat deeper. The total depth below sea level to the mantle is plotted in Figure 13; here it becomes more obvious that the mantle depths take an abrupt drop at about 13-1/2°N, from a mean of 8.4 km in the southern sector to 9.5 km in the northern sector. This coincides with the approximate position of an unnamed fracture zone (originally drawn by Menard) which we will here refer to as the Guerrero Fracture Zone. The anisotropy solution shown is, incidentally, one obtained only from data south of the fracture zone. The solution that includes data on both sides is definitely no better.

INTERPRETATION

The results of this expedition can be simply stated, and are listed in Table 1. At station 4-5, in the Guatemala Basin in the center of the Cocos Plate, the mean depth to mantle is 8.18 km, the mean velocity is 8.02 $\pm$ 0.057 km/sec (standard deviation), with anisotropy $\pm$ 0.210 km/sec, or 5.2% total variation. The high velocity vector is at azimuth 053°. At station 4-8, northwest of the Tehuantepec Ridge and closer to the axis of the East Pacific Rise, the depth to mantle is 8.35 km south of the Guerrero Fracture Zone, and 9.46 km north of the fracture zone. The mean mantle velocity is 8.14 $\pm$ 0.128 km/sec, with anisotropy $\pm$ 0.207 km/sec, or 5.1% total variation. The high velocity vector is at azimuth 029°. Because of the large standard deviation of the mean velocity on this station, no great faith can be placed in either the amount or direction of the anisotropy solution.

During the time that we were at sea gathering the data described above, a paper appeared by Herron (1972) containing a great deal more magnetic data than had previously been available (Figure 14). In this work, she drew some rather tentative lineations in the Guatemala Basin, based on extremely low amplitude magnetic anomalies, which show a remarkable northwest-southeast trend. These lineations are shown on an expanded scale on Figure 15, along with the results of the two anisotropy determinations. It will be noted that the direction of the high velocity vector of station IG-4-5 is almost exactly at right angles to Herron's anomalies 9 and older, and the station is located within the area of the anomalous anomalies.

These results are difficult to explain. The direction of the high-velocity vector confirms Herron's rather tenuous interpretation of the low-amplitude anomalies in the Guatemala Basin, if (as elsewhere) the anisotropy is directly related to the magnetic anomaly direction. Similarly directed anomalies have been found

by Anderson in the Nazca Plate to the south (personal communication), but there are no known anomalies or spreading centers with such a large angle to the north-south direction anywhere else in the eastern equatorial Pacific. One could dismiss the problem by saying that the matching anomalies were approximately at the equator near 120°W, and cannot be seen--but there are a set of anomalies of corresponding age at 15°S, 135°W that are clearly north-south in orientation, which cannot be reconciled.

The only reasonable alternative explanation for the anomaly band and the anisotropy direction in the Guatemala Basin is, therefore, rotation of the small Cocos Plate, due to the influence of the nearby consumption zone on relatively small remnant plates.

The relatively poor results obtained on station IG-4-8 are possibly explainable due to the same mechanism. If the plate had indeed rotated about a pole close to its own northern tip, the anisotropy station (located close to the position of anomaly 5 on Herron's chart) would have straddled a large number of anomalies of differing direction, and should indeed have produced scattered data.

Alternatively, we could interpret the results as indicative of the absolute motion of the plate. In this case, station 4-5 agrees closely with Jason Morgan's (1972) vector for absolute motion of the Cocos Plate. We could, then, consider the Tehuantepec and Cocos Ridges as indicators of the absolute plate movement. If this interpretation is correct, however, we would have problems with the older Cocos Plate station close to the Galapagos triple junction which indicates east-west movement in recent time, and the work north of Hawaii which definitely does not line up with Morgan's directions of absolute motion of the Pacific Plate as derived from the Hawaiian hot spot. Perhaps the Hawaiian hot spot is moving!

Work by Carter et al. (1972) has shown that the mantle anisotropy we observe can be created by syntectonic recrystallization of a peridotitic mantle at the Mohorovicic discontinuity close to a

spreading center. The high velocity vector in the uppermost mantle will, in this case, lie in the direction of principal shear between the superjacent lithosphere and the aesthenosphere below. If lithospheric plates move over a static aesthenosphere by any mechanism, pushing from a spreading center, pulling from a subduction zone, gravity sliding down the flank of a ridge, or even riding on a moving aesthenosphere, the anisotropy high velocity vector should point in the direction of absolute motion of the plate. Unfortunately, it does not--at least not in the direction of "absolute motion" given by Jason Morgan (1972). Nor does it point in directions radial about a "plume" or "hot spot". Instead, it quite uniformly points in a direction perpendicular to magnetic anomalies.

The extremely shallow depth to mantle under station 4-5 and the southern part of 4-8 should be noted. The crust itself is thinner than normal--but is within one standard deviation of the mean for the Pacific Basin. What is unusual is to find mantle this shallow in water this shallow in an area of normal mantle velocity and normal heat flow. This is the sort of location that we would have like to find for the Mohole site. The only explanation for this anomaly is that for some reason the surface of this plate is cooler than normal--but high temperature at depth (resulting in shallow sea floor and shallow mantle) has not yet resulted in heating of the sea floor itself.

ACKNOWLEDGMENTS

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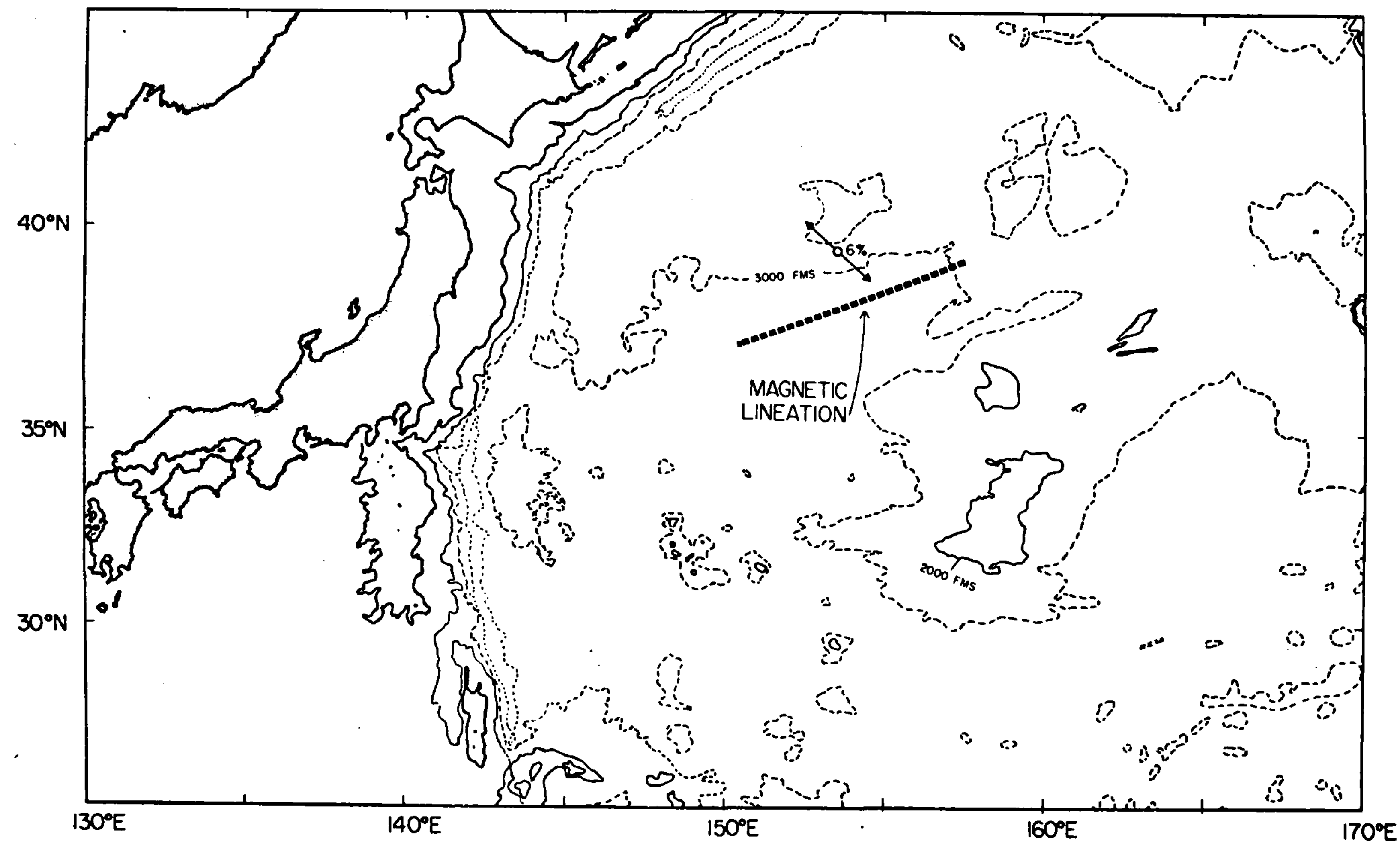
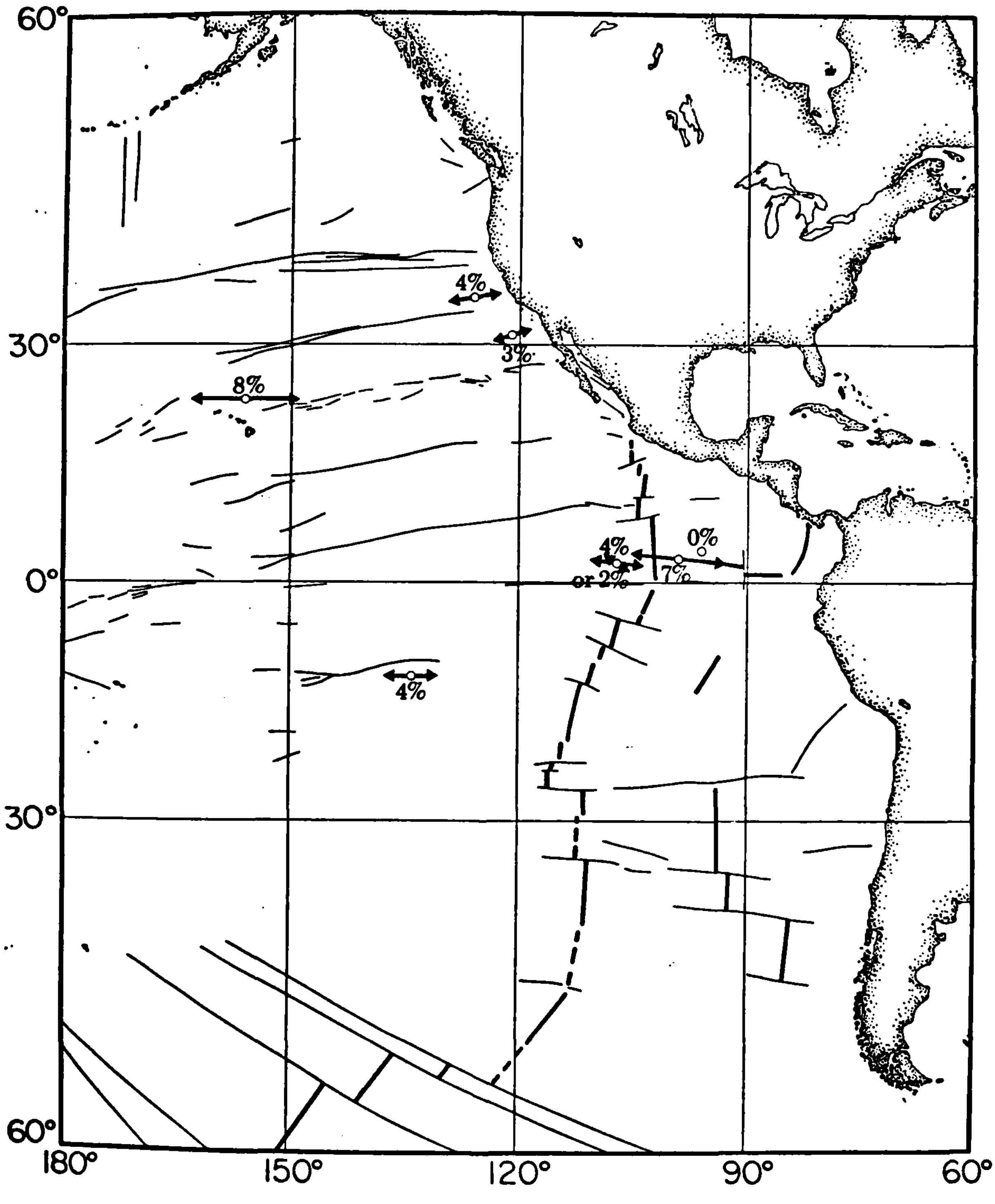
Table 1. Cocos Plate Anisotropy

Station	Latitude	Longitude	Mantle Depth	Mean Velocity	Anisotropy km/sec	Anisotropy %	Anisotropy Azimuth	Quality
IG-4-5	9.0°N	91.7°W	8.18 km	8.02 ± 0.057	0.420	5.2	053°	Good
IG-4-8	13.5°N	99.5°W	N. 9.46 km S. 8.35 km	8.14 ± 0.128	0.414	5.1	029°	Poor

FIGURE CAPTIONS



40°N
35°N
30°N
130°E
140°E
150°E
160°E
170°E
MAGNETIC LINEATION
3000 FMS
2000 FMS
6%



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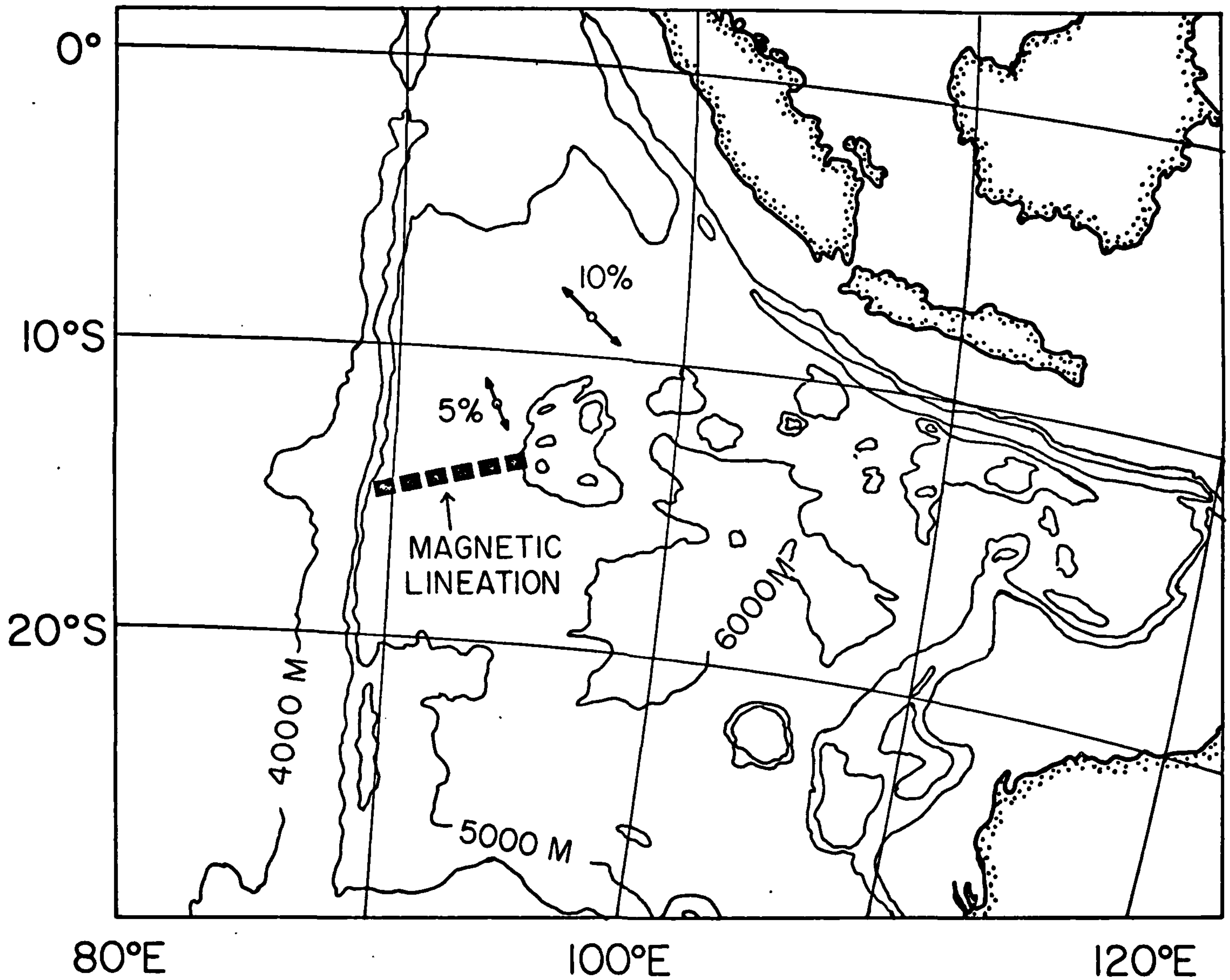
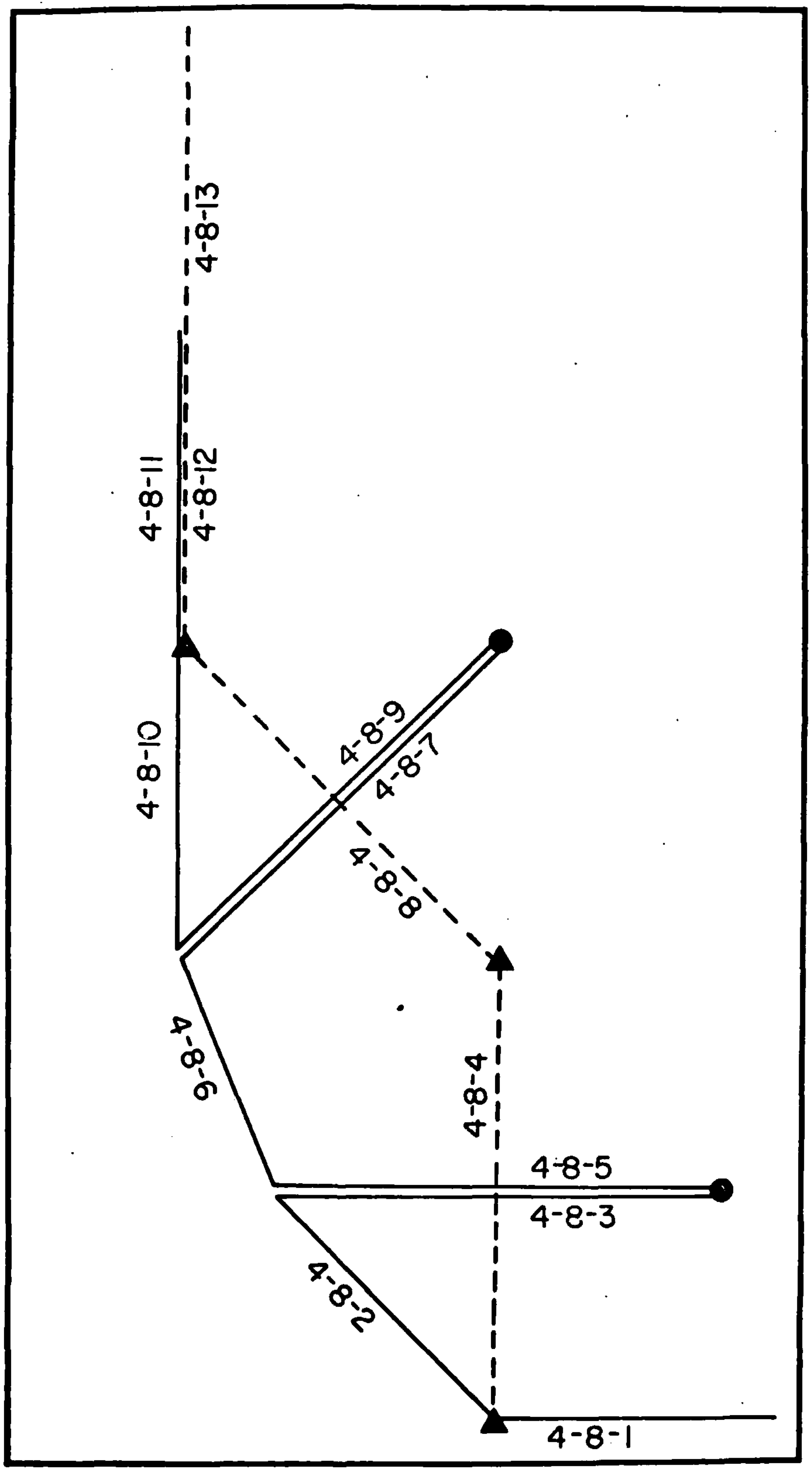

0°
10°S
20°S
80°E
100°E
120°E
10%
5%
MAGNETIC
LINEATION
6000M
5000 M
4000 M

fig.:

Fig. 4



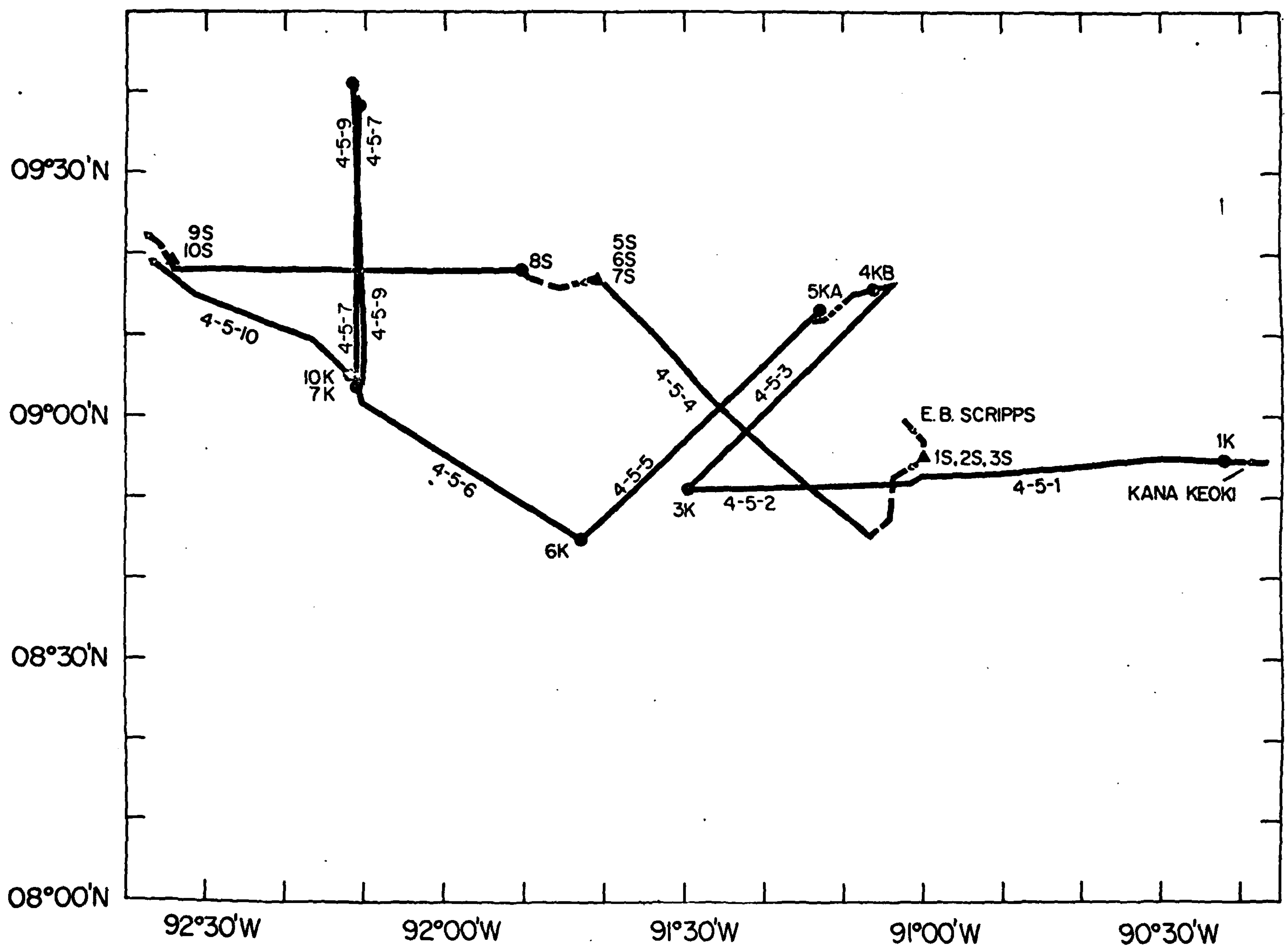
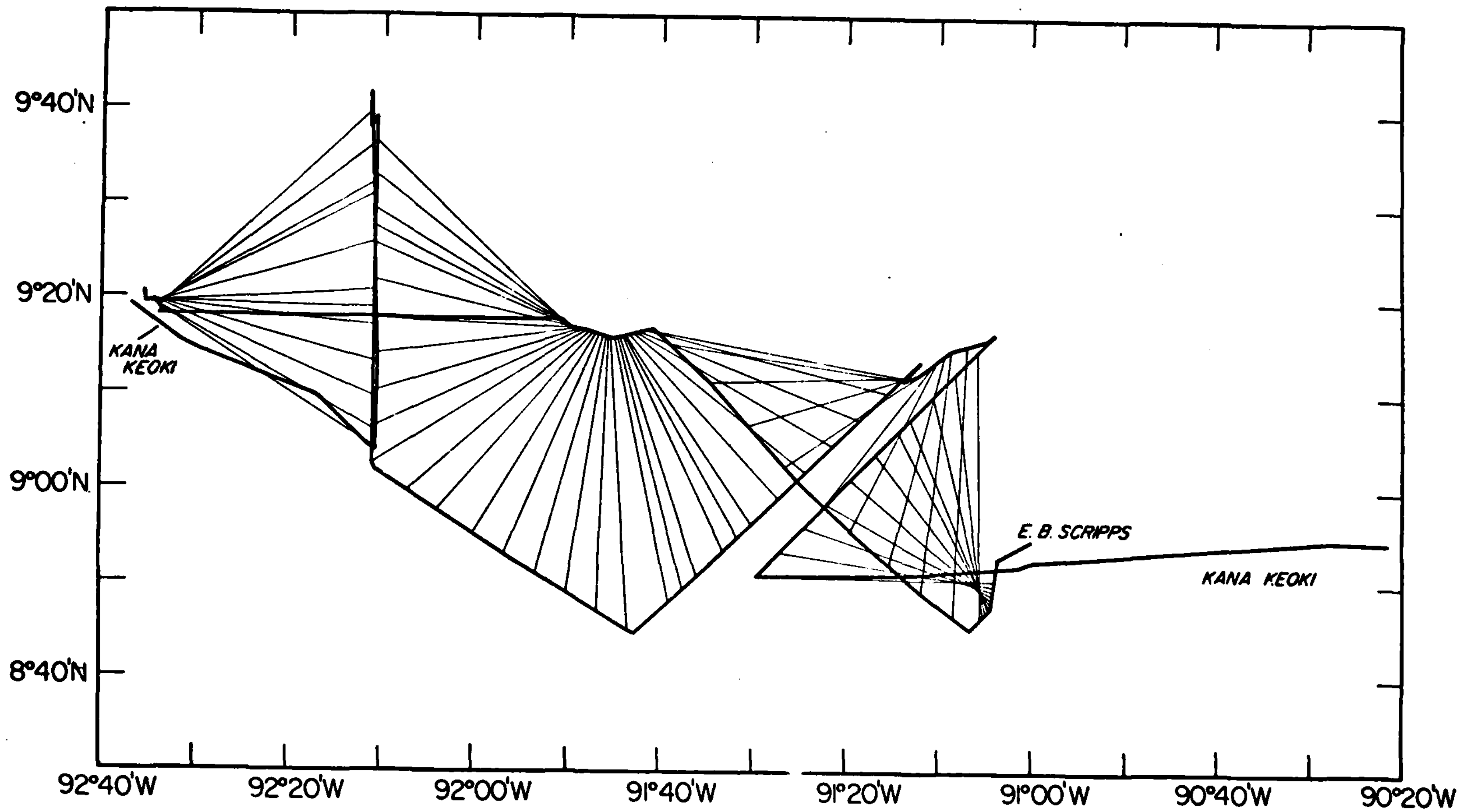

09°30'N
09°00'N
08°30'N
08°00'N
92°30'W
92°00'W
91°30'W
91°00'W
90°30'W
9S
10S
8S
5S
6S
7S
5KA
4KB
4-5-9
4-5-7
4-5-10
10K
7K
4-5-6
6K
4-5-5
4-5-4
4-5-3
3K
4-5-2
E. B. SCRIPPS
1S, 2S, 3S
4-5-1
1K
KANA KEOKI

fig 5


9°40'N
9°20'N
9°00'N
8°40'N
92°40'W
92°20'W
92°00'W
91°40'W
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91°00'W
90°40'W
90°20'W
KANA KEOKI
E. B. SCRIPPS
KANA KEOKI

fig. 6

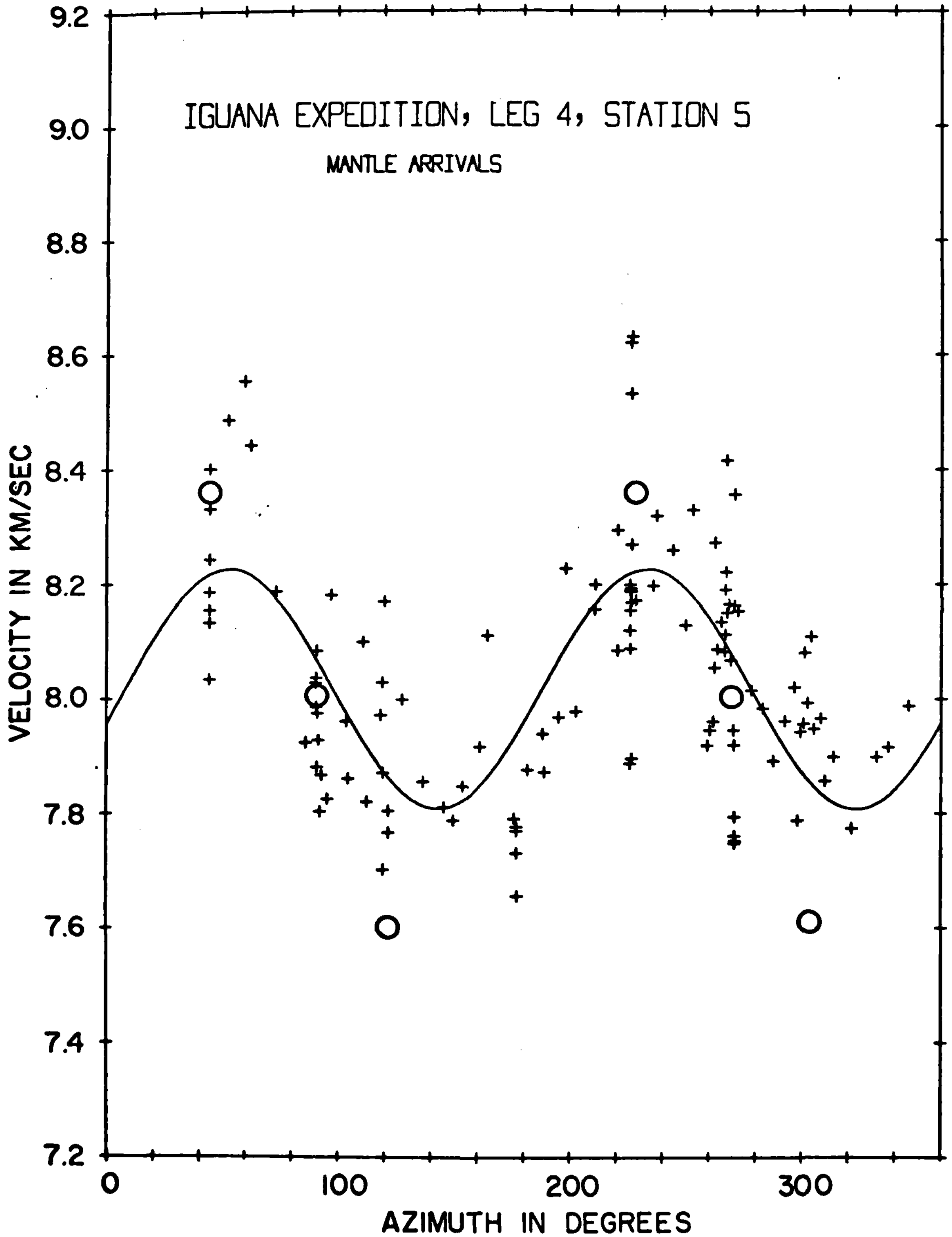
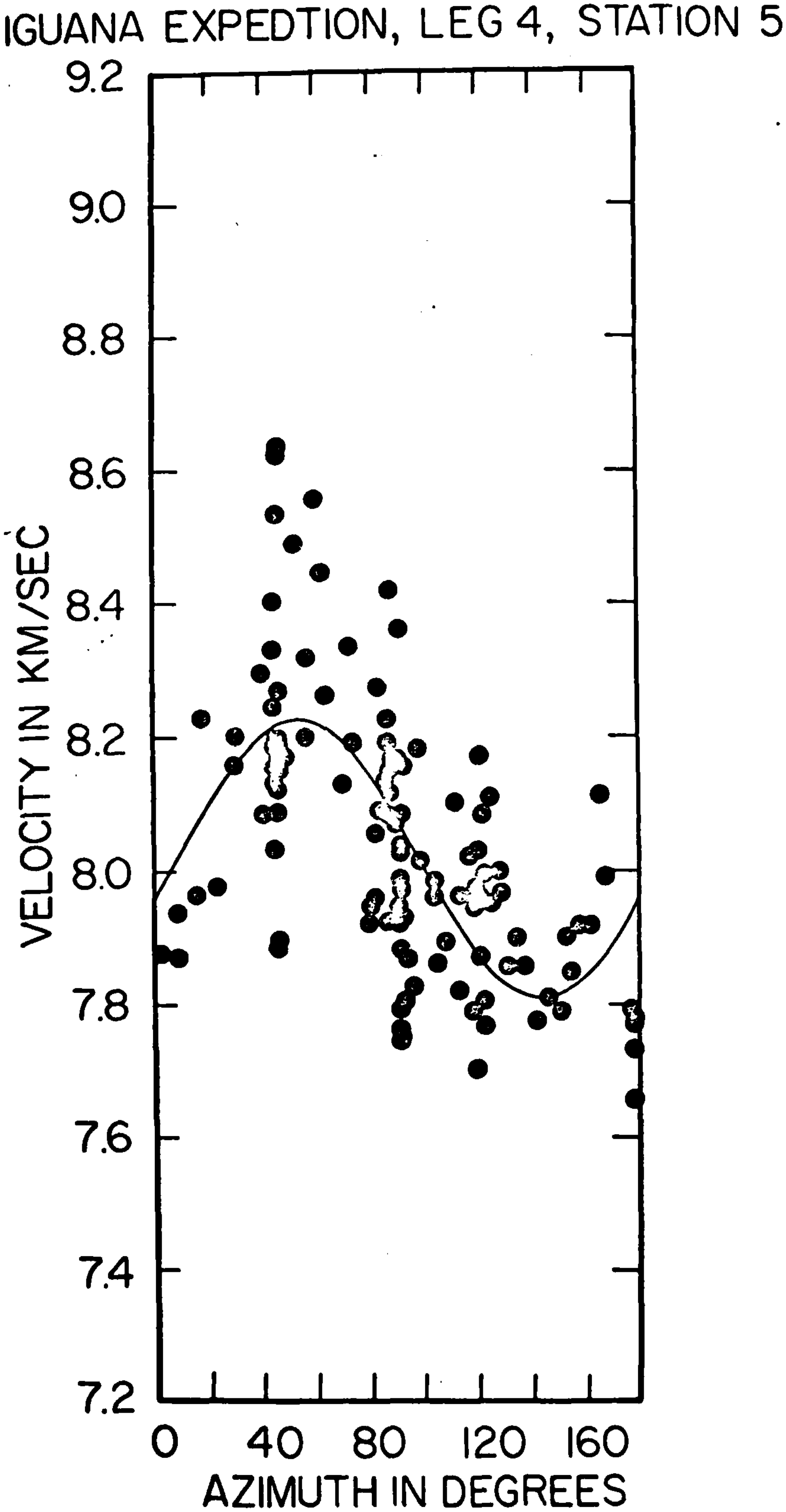
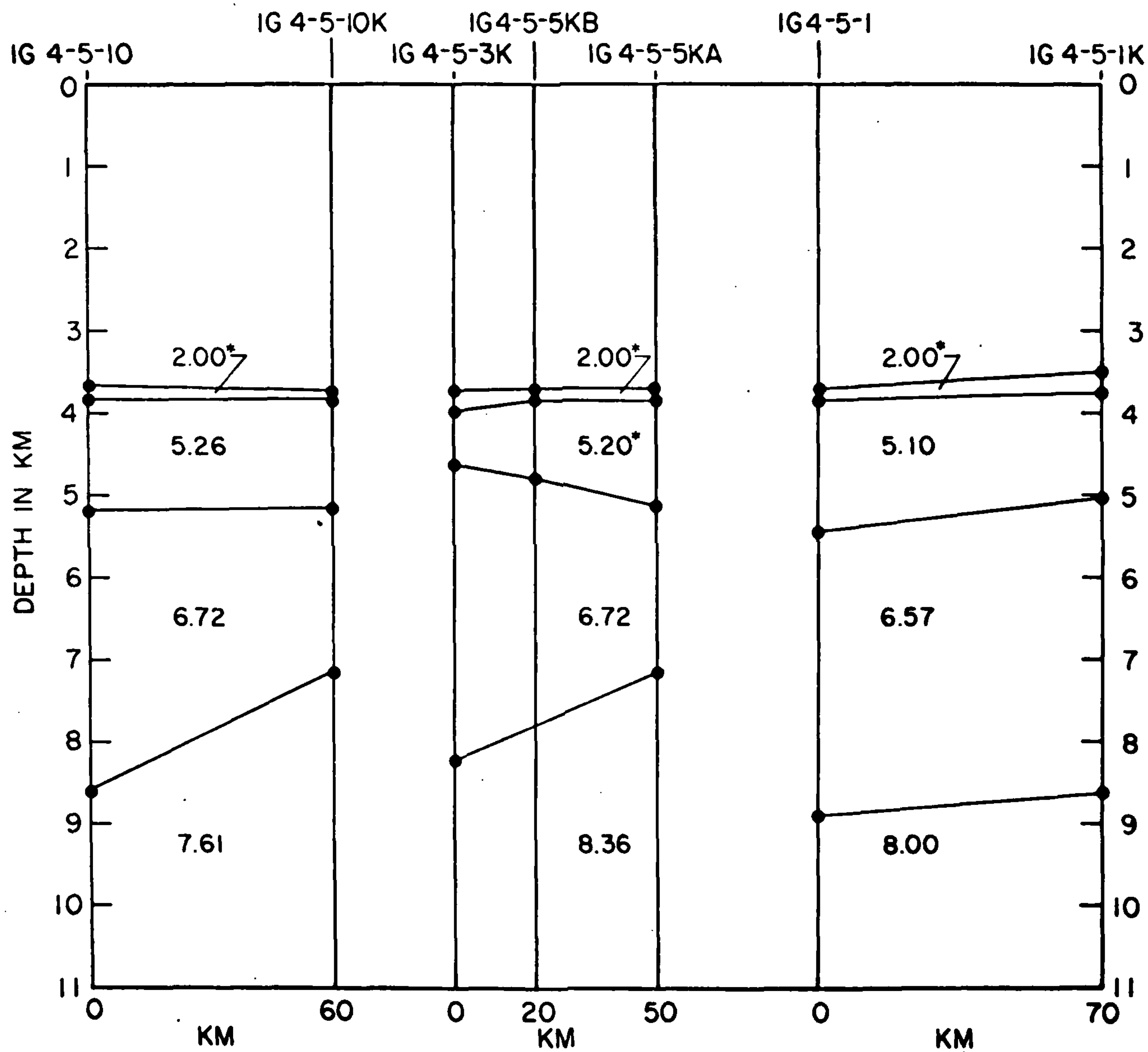

IGUANA EXPEDITION, LEG 4, STATION 5
MANTLE ARRIVALS
VELOCITY IN KM/SEC
AZIMUTH IN DEGREES
9.2
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
0
100
200
300

Fig. 7



IGUANA EXPEDTION, LEG 4, STATION 5
VELOCITY IN KM/SEC
9.2
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
0
40
80
120
160
AZIMUTH IN DEGREES

fig 8



IG 4-5-10
IG 4-5-10K
IG 4-5-3K
IG4-5-5KB
IG 4-5-5KA
IG4-5-1
IG 4-5-1K
DEPTH IN KM
0
1
2
3
4
5
6
7
8
9
10
11
2.00*
5.26
6.72
7.61
2.00*
5.20*
6.72
8.36
2.00*
5.10
6.57
8.00
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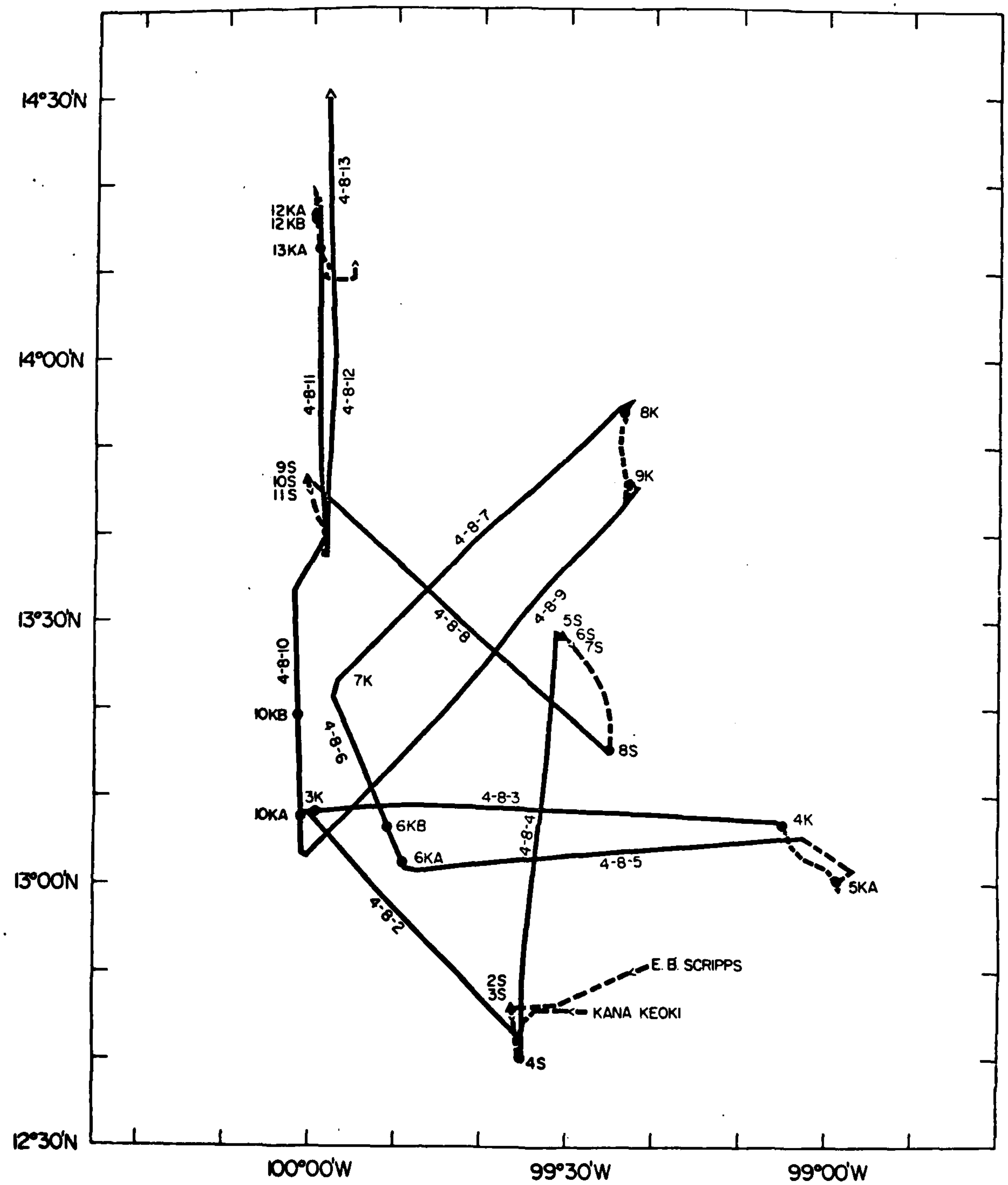
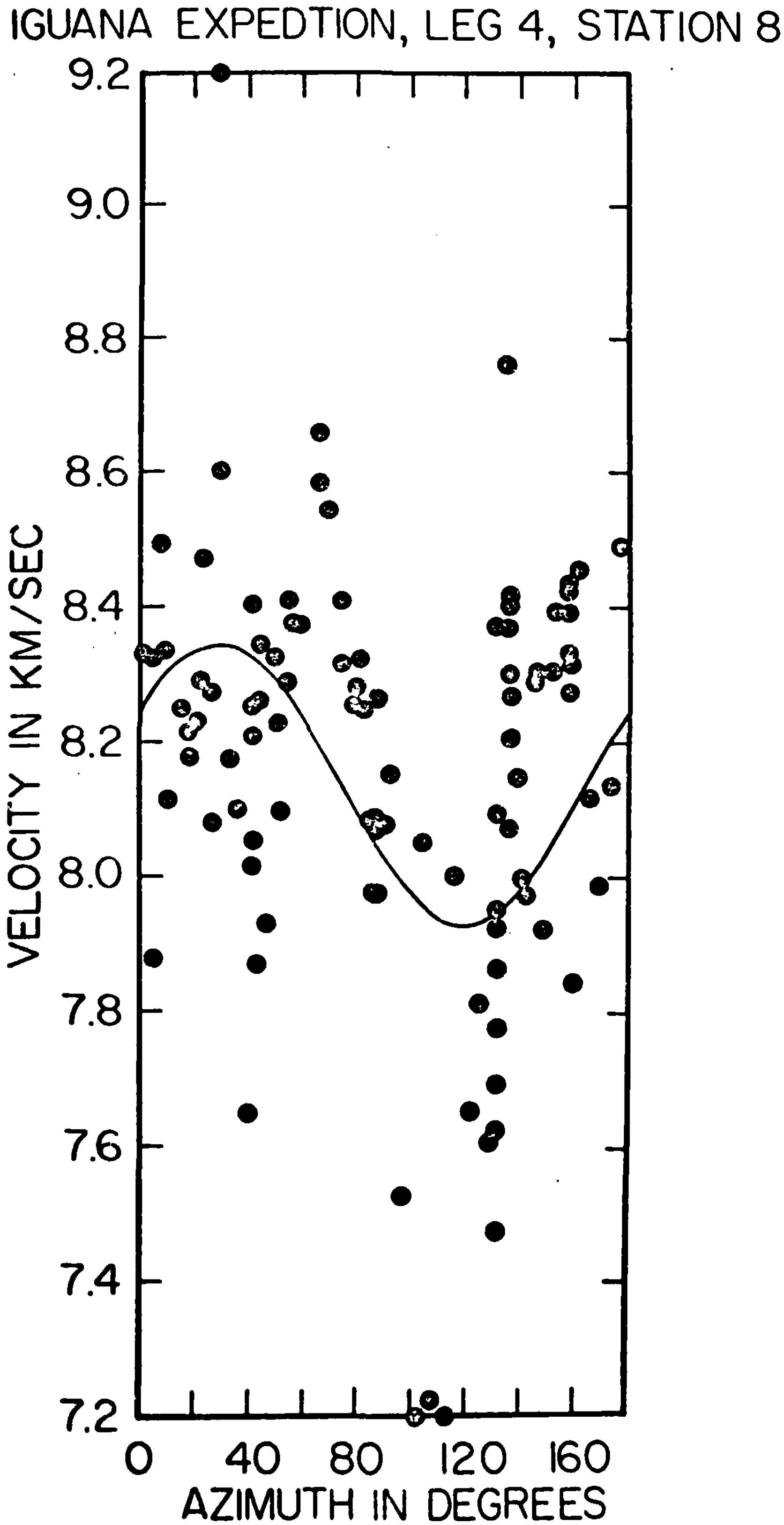
60
KM
0
20
50
KM
0
70
KM

Fig. 9



14°30'N
14°00'N
13°30'N
13°00'N
12°30'N
100°00'W
99°30'W
99°00'W
4-8-13
12KA
12KB
13KA
4-8-11
4-8-12
8K
9S
10S
11S
9K
4-8-7
4-8-9
4-8-8
5S
6S
7S
4-8-10
7K
10KB
4-8-6
8S
3K
4-8-3
10KA
6KB
4K
4-8-4
6KA
4-8-5
5KA
4-8-2
E. B. SCRIPPS
2S
3S
KANA KEOKI
4S

Fig. 10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VELOCITY IN KM/SEC
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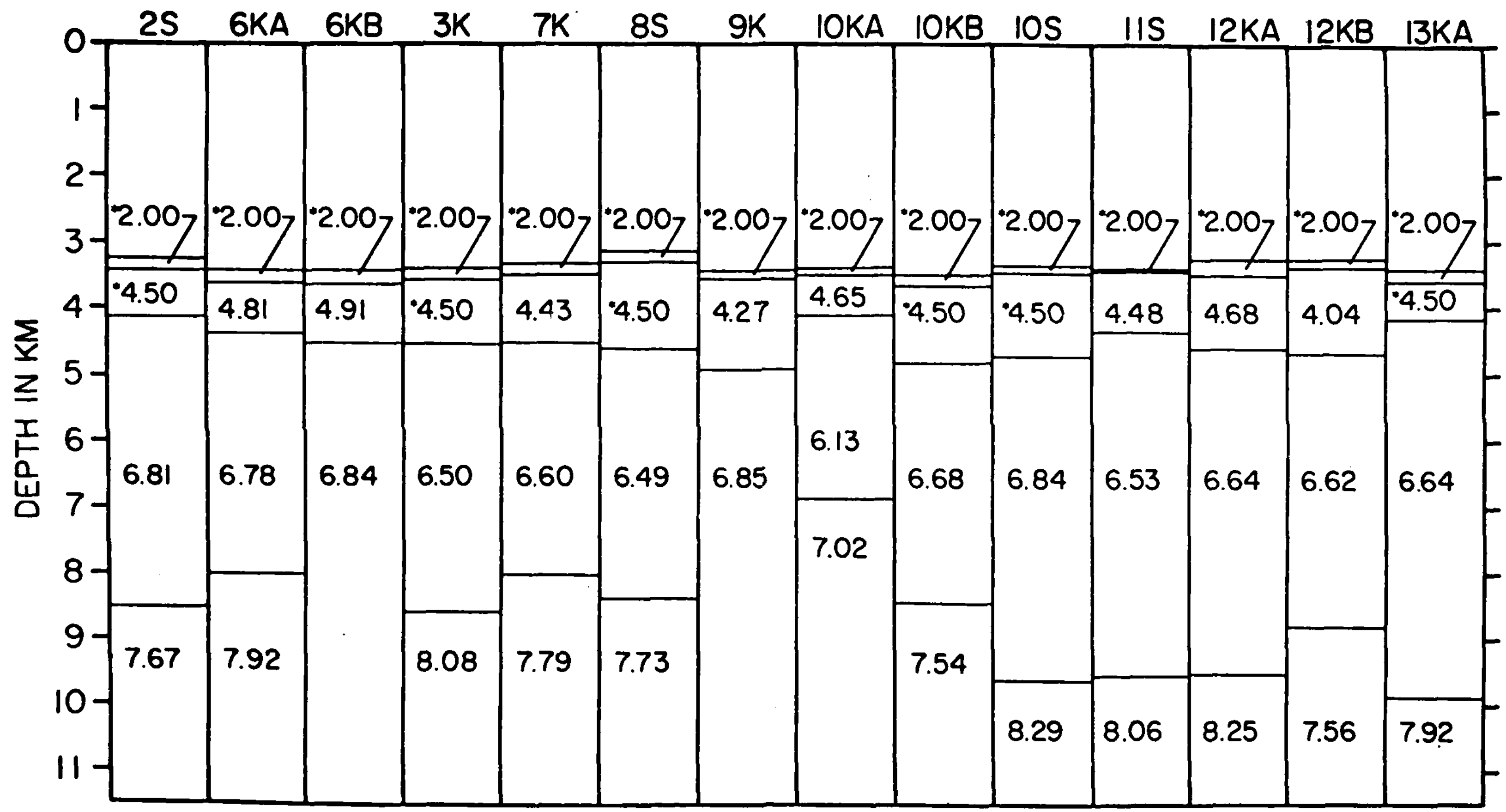
9.0
8.8
8.6
8.4
8.2
8.0
7.8
7.6
7.4
7.2
0
40
80
120
160
AZIMUTH IN DEGREES

Fig. 11



IGUANA 4-8

Fig. 12

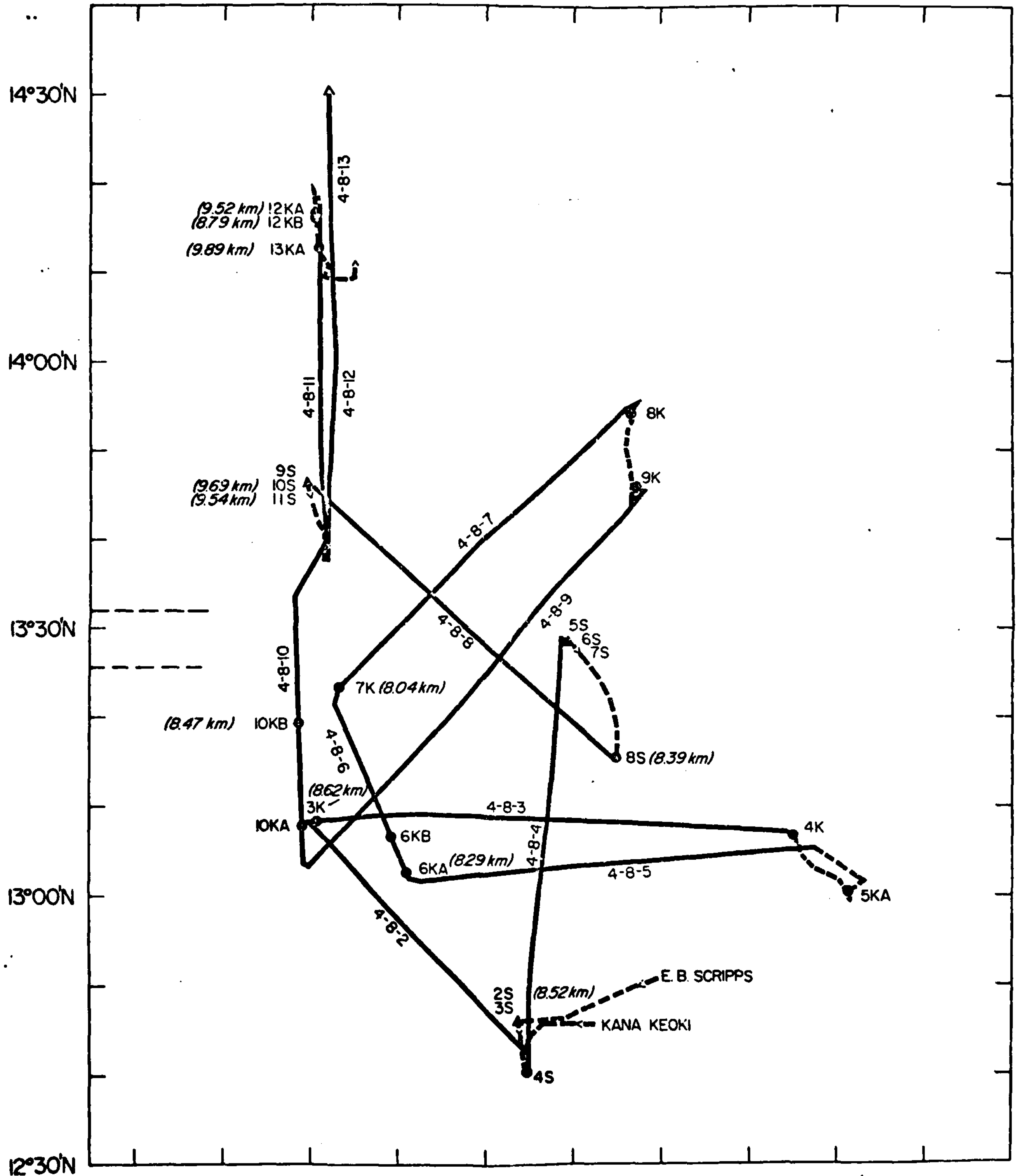
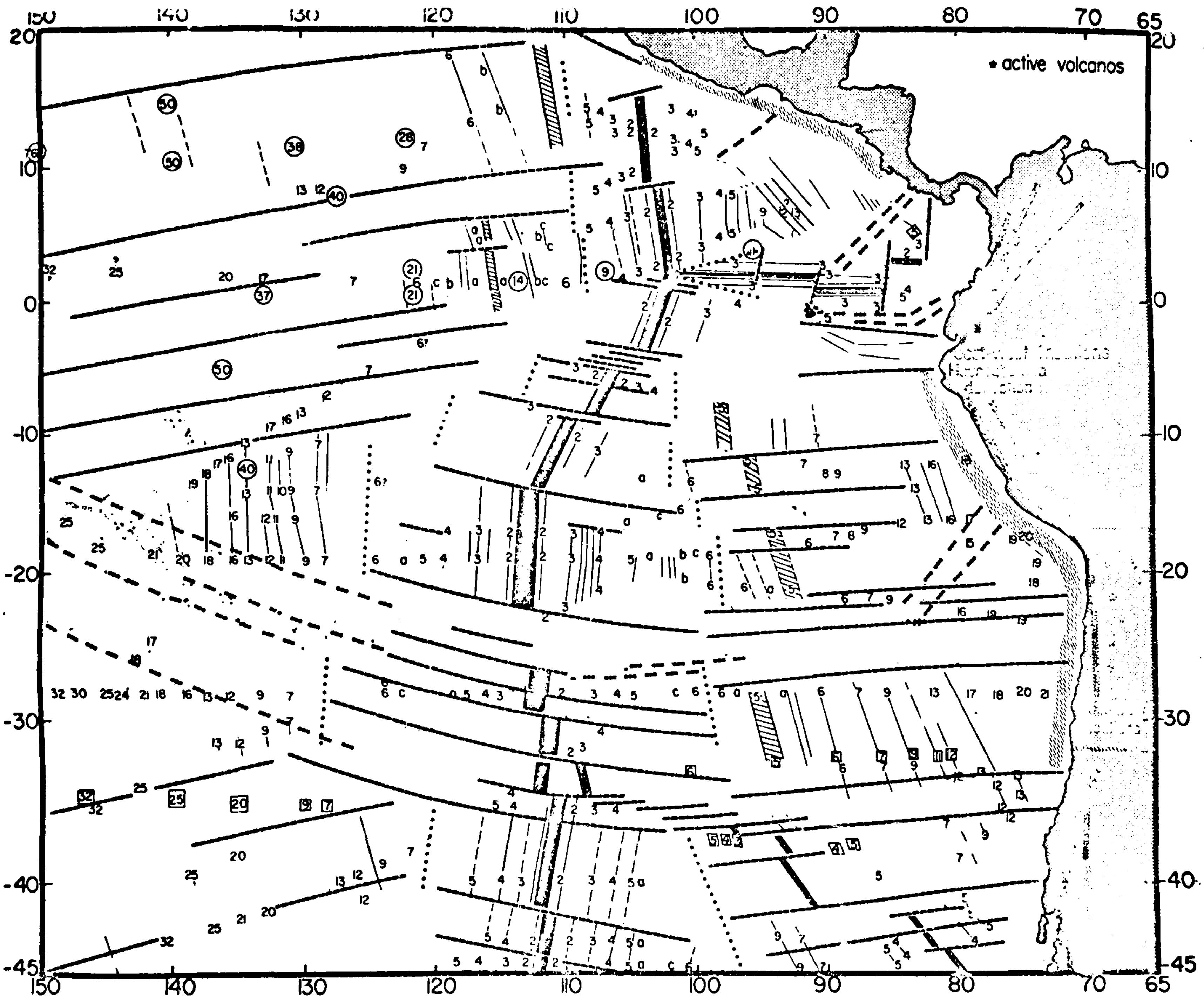

14°30'N
14°00'N
13°30'N
13°00'N
12°30'N
100°00'W
99°30'W
99°00'W
4-8-13
(9.52 km) 12KA
(8.79 km) 12KB
(9.89 km) 13KA
4-8-11
4-8-12
8K
9K
9S
(9.69 km) 10S
(9.54 km) 11S
4-8-7
4-8-9
4-8-8
5S
6S
7S
4-8-10
7K (8.04 km)
(8.47 km) 10KB
8S (8.39 km)
4-8-6
(8.62 km)
3K
4-8-3
4K
10KA
6KB
6KA (8.29 km)
4-8-4
4-8-5
5KA
4-8-2
E. B. SCRIPPS
2S
3S
(8.52 km)
KANA KEOKI
4S

Fig. 13


* active volcanos